Gravity and Magnetic Fields Over the Proposed Moho Hole Site North of Maui[1]

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DURING 1964 the Hawaii Institute of Geophysics carried out two marine surveys of the area north of Maui. These surveys provided the gravity, magnetic, and bathymetric data which will be discussed in this paper. The first survey was made by J. C. Rose on the Bureau of Commercial Fisheries ship "Charles H. Gilbert," using a LaCoste-Romberg shipboard gravimeter loaned by the University of California at Los Angeles. The second was conducted under a cooperative program with the U. S. Coast and Geodetic Survey on the hydrographic survey ship "Surveyor," under the command of Captain R. Jones with Mr. Kenneth Culler representing the Hawaii Institute of Geophysics. Position points along the tracks of these operations are shown in Figure 1.

Subsequently, there have been two magnetic measuring cruises on the Hawaii Institute of Geophysics vessel R/V "Teritu."

PREVIOUS STUDIES

Many earlier studies have been made of the gravity and magnetic fields in the vicinity of the Hawaiian Islands. Most of the early work was confined to submarine gravity measurements, starting with the pioneer round-the-world trip of Vening Meinesz in 1925 and continued by the Lamont Geological Observatory in the years immediately following World War II. The operations made on the U. S. submarines "Capitaine," SS 336; "Sea Dog," SS 401; "Bugara," SS 331; and "Rock," SS 274 were by various observers, but mostly by Dr. J. L. Worzel. The subsequent surface ship operations involving both gravity and magnetic observations were made by the "Argo," operated by the Scripps Institution of Oceanography, which carried out local surveys during cruises Monsoon and Dodo while on her way to participate in the International Indian Ocean Expedition. One of the authors (Belshé) was aboard during both of these operations, and the other participated in the second. Measurements have also been made by the "Rehoboth" operated by the U. S. Navy Oceanographic Office, and by the "Surveyor" and the "Pioneer" operated by the U. S. Coast and Geodetic Survey. During the spring 1964 operation of the "Surveyor," Dr. P. Dehlinger of Oregon State University was in charge of the gravity program. The authors are indebted to all these groups for their cooperation in making available the information from these cruises.

Most, but not all, of the gravity information from these earlier studies has been used in the gravity analysis presented in the paper in this issue by Strange et al. (p. 381 in this issue). It can be seen from Figure 2 that detailed coverage in the area of immediate interest (centered on 155°28′W, 22°22′N) is not as good as one might wish, although probably adequate for present purposes—the determination of the gross field and any significant abnormalities in the crust or mantle in the general area of the proposed Moho Hole site.

NARRATION OF THE "GILBERT" OPERATION

Arrangements were made in May 1964 between the Hawaii Institute of Geophysics, the Office of Naval Research, and the University of California at Los Angeles, for the loan of a LaCoste-Romberg sea gravimeter S3 for two weeks.

Through the cooperation of the Bureau of Commercial Fisheries, the ship "Charles H. Gilbert" was made available for the survey. The ship conducted underway gravity and bathymetric observations between 0445Z, May 30, and 1400Z, June 4, 1964. Position points for the ship's track during observations are shown on Figure 1. Because of the relatively small size of the ship and the prevailing sea and wind di-

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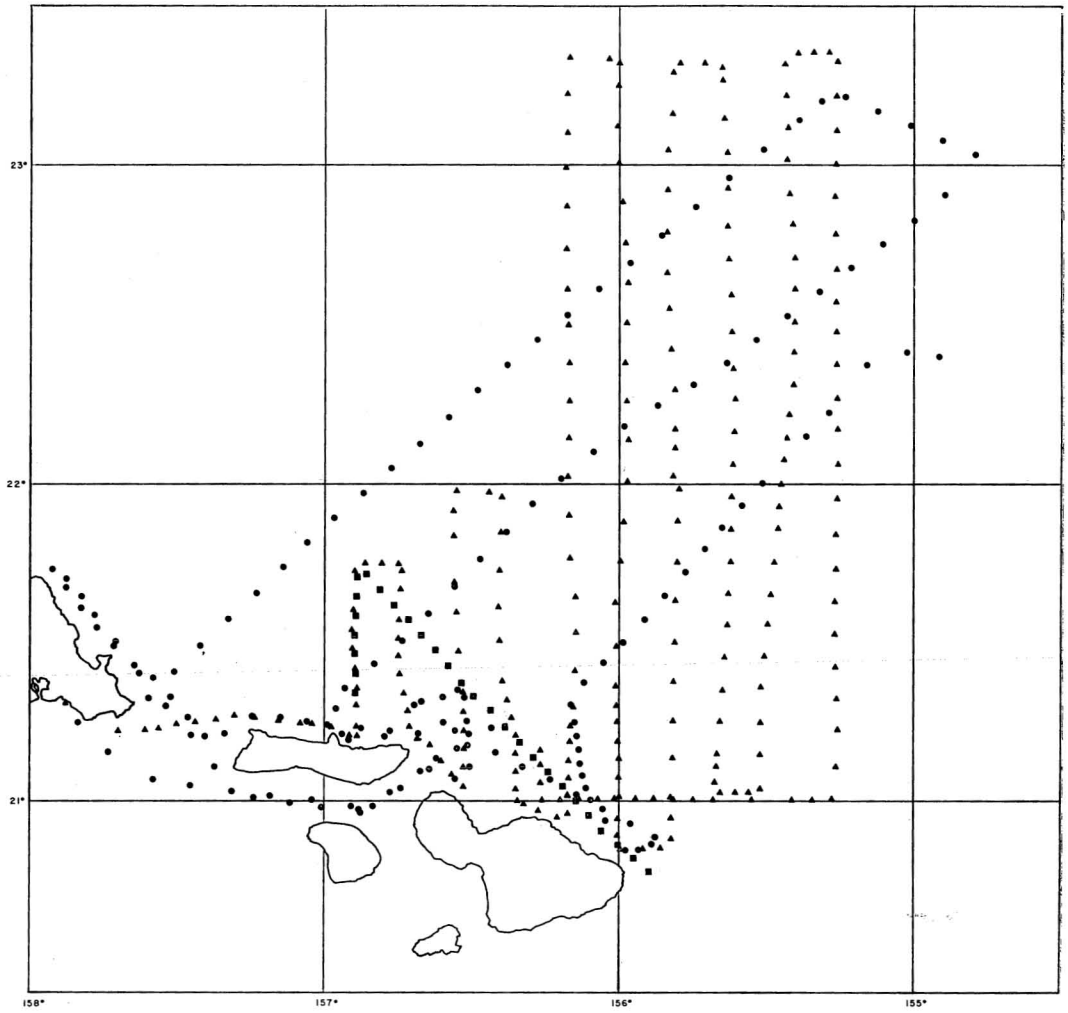

FIG. 1. Position points along the ship's tracks of R/V "Charles H. Gilbert" (*circles*) and of R/V "Surveyor" (*triangles* and *squares*).

rection, northeast-southwest tracks were chosen. This heading also resulted in the profile tracks being perpendicular to the structural strike of the Hawaiian Swell. Sea conditions were unusually calm during the entire cruise, allowing approximately 1000 miles of gravity observations out of approximately 1170 miles of total cruise. A note of unusual interest is that for the three crossings of the Molokai channel (usually characterized by confused high seas) the seas were abeam, yet the Browne correction was only 200 mgal on the last crossing and less than 100 mgal on the first two crossings.

The Browne corrections for the long southwest–northeast tracks were approximately 300, 200, and 400–600 mgal for the west, central, and eastern tracks, respectively. The central and eastern tracks had following seas. The tracks close to the islands generally had total Browne corrections of approximately 100 mgal.

Bathymetry was obtained from the "Gilbert's" fathometer to 250 fm, and from E. L. Hamilton's 1953 and 1954 (unpublished) bottom contour charts northeast of Oahu, and F. P. Shepard's (unpublished) bottom contour charts of Kaneohe Bay and of the north coast

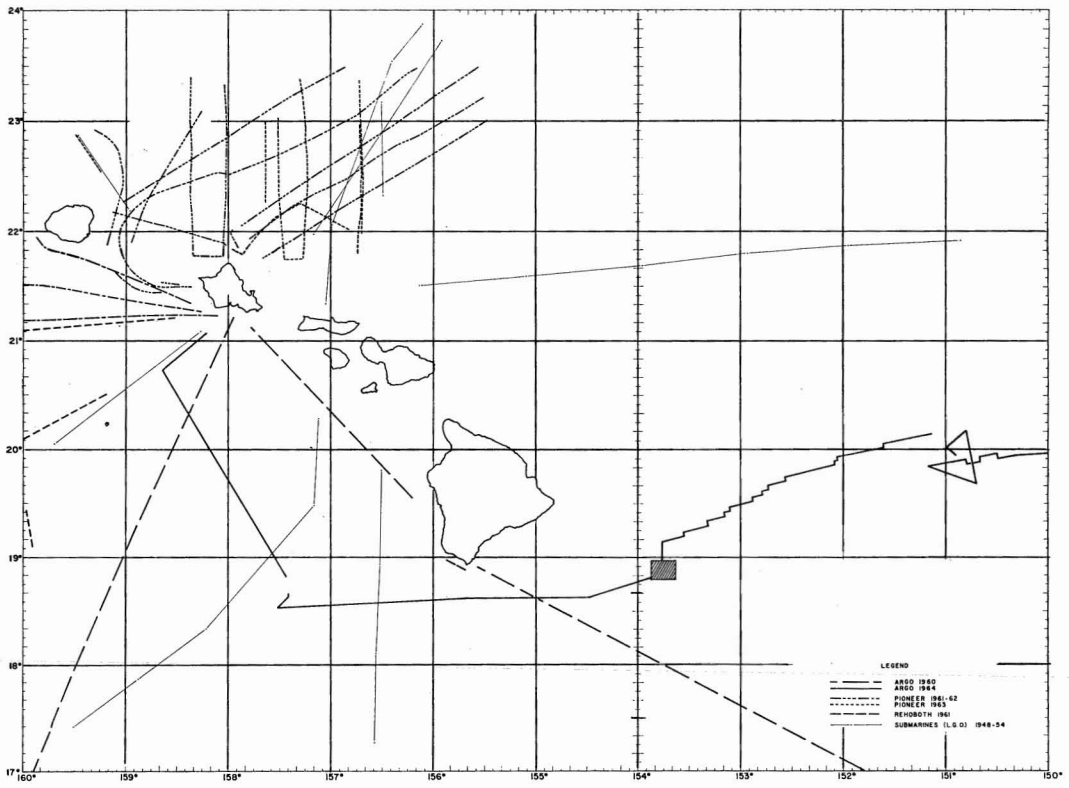

FIG. 2. Ship's tracks of gravity and magnetic studies in the Hawaiian Islands area performed by vessels other than R/V "Charles H. Gilbert" and R/V "Surveyor."

of Molokai. Additional information was obtained from the preliminary BC 1604 and BC 1605N charts of the U. S. Navy Oceanographic Office. Corrections were made for sound velocity in Hawaiian waters using a temperature vs. depth curve derived from data in Seckel (1955), McGary (1955), Seckel (1962), and Muromtsev (1963), and from the tables of sound speed in sea water (U. S. Naval Oceanographic Office, 1962).

The speeds used on any one straight track were weighted means, weighted according to the time interval between successive position fixes. Ship's position was determined from Loran C as well as radar and visual fixes.

Gravity results were computed on the University of Hawaii IBM 7040 computer, using an adapted program obtained from M. D. Helfer of the University of California at Los Angeles.

NARRATION OF THE "SURVEYOR" OPERATION

The "Surveyor" conducted underway gravity, magnetic, and bathymetric observation in the area north of Maui from 2110Z, September 28, to 2026Z, October 2, 1964. Position plots for the ship's track during this survey are shown on Figure 1. The tracks define a series of north–south lines spaced approximately 10 miles apart. Six long lines centered on 155°45′ W give good coverage of the area 120 miles north of Maui, over the Hawaiian Arch, where Shor and Pollard (1964) report depths to the mantle of about 9 km. West of this area four shorter lines cover an area 20 miles north of Molokai and Maui, where Shor and Pollard (1964) report sub-Moho seismic velocities at depths of 5.8–7 km. This area is also characterized by a large positive magnetic anomaly (Malahoff and Woollard, in a forthcoming issue

of *Pacific Science*) centered over the island shelf at a depth of 500 m.

The gravity measurements were made with the LaCoste-Romberg sea gravimeter S12. Magnetic measurements were taken with a direct reading proton precession magnetometer, Varian model V4931DR. A narrow beam vertical sonar array produced by the Harris Company was used as the precision echo sounder for bathymetry. Navigation information relied heavily on Loran C for distant coverage and radar and visual observations when near the islands.

The ship's position was plotted every 15 minutes during most of the cruise (Figure 1). Data (time, depth, gravity, and magnetic force) were logged every minute. The depth information was read in fathoms from a precision graphic recorder. Its accuracy is ± 1 fm (± 1.83 m). The time was recorded digitally on the minute from a crystal-controlled clock and should be accurate to ± 3 sec. The total force of the magnetic field was recorded to an accuracy of ± 1 gamma from a digital frequency meter.

The gravity measurements consisted of four record sets. The beam position of the heavily damped gravimeter was averaged over a 3½-minute interval and presented digitally by a computer. The average beam position and the average meter counter setting were displayed graphically on a potentiometer recorder. Two pairs of galvanometer recorders displayed the short-period and long-period ham records, showing the nature of the horizontal accelerations affecting the instrument.

The digital data for time, magnetism, and gravity were recorded every minute, on the minute, by a Friden paper tape perforator in a B.C.D. form. This data tape could be printed out on a Flexowriter; an example is shown as Figure 3. The paper tape generated during the cruise was converted to a magnetic tape using the 1401 computer at the Statistical and Computing Center of the University of Hawaii, and the magnetic tape was then used directly in data processing with the IBM 7040 computer. Navigational control data, including the ship's heading and speed, and depth data were provided from a second magnetic tape which was generated from punched cards prepared at the end of the cruise.

In the data processing program depths in fathoms were converted to meters and then corrected for sound velocity variations by an interpolation formula. The gravity value was an average value centered at 105 sec before it was recorded. The magnetic value represented a spatial point where the ship had been approximately 30 sec earlier than the time of recording. Therefore, both the recorded gravity and magnetic values were adjusted by simple averaging to correspond in real time to the depth record. The magnetic values were corrected for ship's heading and diurnal variation (using records from the magnetic observatory operated by the U. S. Coast and Geodetic Survey at Ewa Beach, Oahu). The observed gravity values were computed after the instrument variations were adjusted to the base value established by ties to the absolute gravity base site at Honolulu on September 21 and October 11. (The drift between these ties was 0.7 mgal.) The Eotvos correction term, using the ship's course and speed, was incorporated in the computation.

The computed values for depth, gravity, free-air gravity anomaly, and magnetic force were printed out by the computer in one-minute intervals. These values were also plotted graphically as profiles by a computer plotting program. Figure 4 is an example of such a plot for the

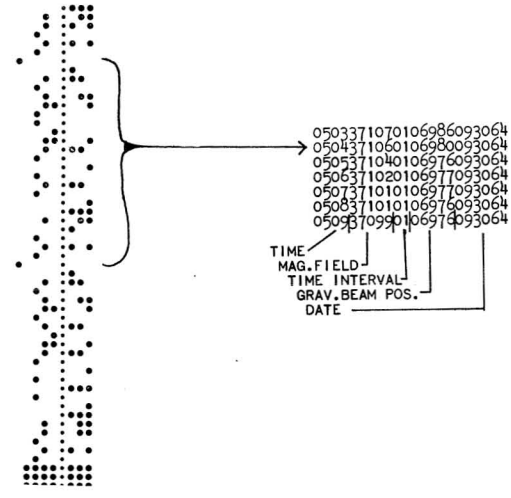

FIG. 3. Perforated paper data tape from R/V "Surveyor."

most westerly of the long north–south tracks. On these plots time is represented as a sequential minute number beginning at 2110Z, September 28. This particular plot follows 156°10′ W, and extends from 20°56′N to 23°20′N. The depth record begins on the shelf north of Maui, shows the drop into the deep, and rises onto the Arch, where it terminates. Negative excursions on the free-air anomaly curve, as are seen at time numbers 1580 and 1730, represent erroneous readings caused by excessive acceleration corrections and are related to changes in ship speed.

DISCUSSION OF COMBINED RESULTS

In constructing the free-air anomaly contour map of the Moho Hole site area (Fig. 5), gravity results for the "Surveyor" north–south track were arbitrarily adopted as control data for correction of the other data. The first step was to correct the cross-cutting "Gilbert" lines of measurements. These in turn were used to correct the south–north "Surveyor" tracks. The adoption of the quartering sea north–south tracks as a control is in accord with results reported by Dehlinger (in press). The corrections adopted were −9, +7, and −23 mgal for the west, central, and eastern "Gilbert" long lines, respectively, and +15 mgal for each of the three south–north "Surveyor" lines. No adjustments were made for the lines close to the islands, as the Browne corrections were generally 100 mgal or less.

It should be noted that the free-air anomaly

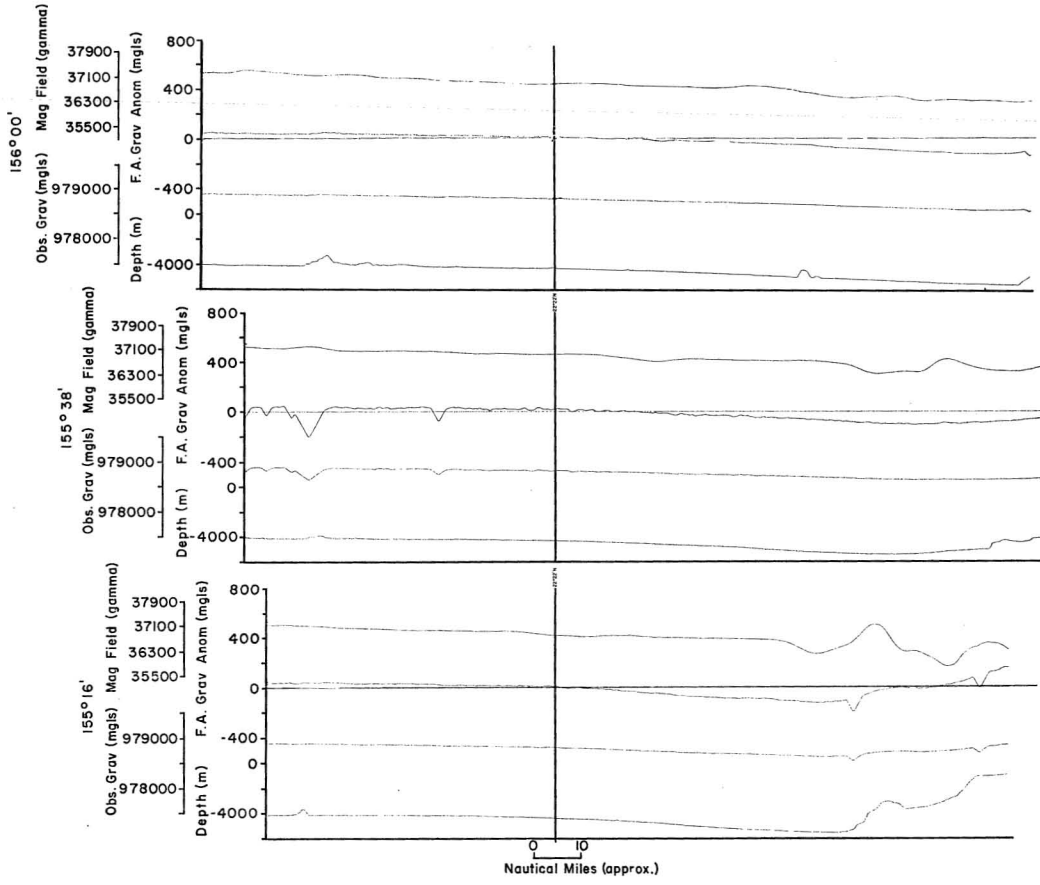

FIG. 4. Computer-plotted profiles of depth, observed gravity, free-air gravity anomaly, and magnetic force along a ship track of R/V "Surveyor."

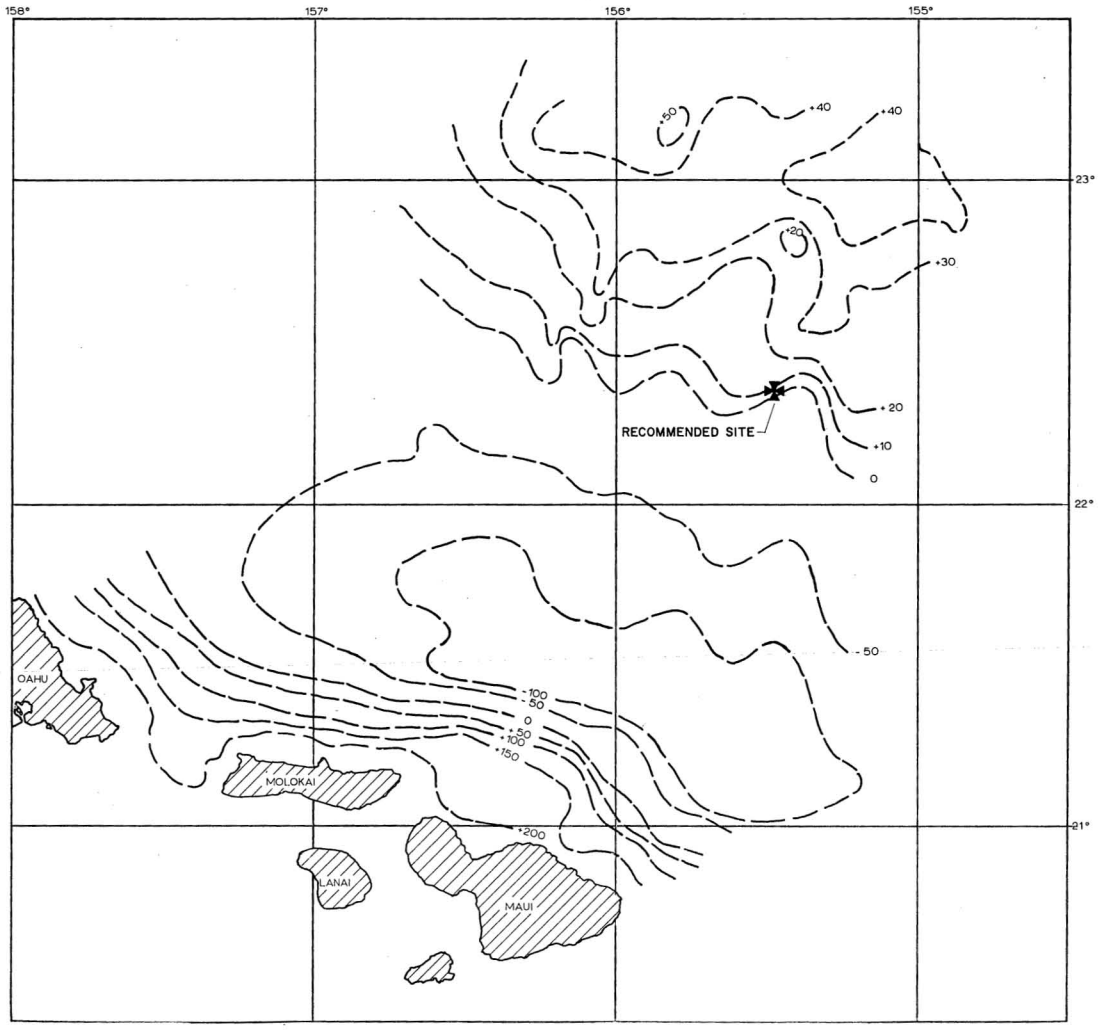

FIG. 5. Free-air anomaly map of the area north of Maui.

map (Fig. 5) differs slightly from the map by Strange et al. (Fig. 3, p. 386 in this issue), and reflects the effect of later detailed data that were not available at the time their map was drawn. The map of the total magnetic field north of Maui is given as Figure 2 in the paper by Woollard in this issue (see p. 282).

Figure 4 shows three profiles made by the "Surveyor" as north–south runs. The proposed Moho Hole site lies midway between the profiles following 155°38′W and 155°00′W. The three profiles have been aligned at the point in time where they cross 22°22′N. As indicated by Strange et al., and as shown here, the proposed Moho Hole site lies very near the point where the free-air anomaly changes from a positive field over the Arch to a negative field in the Hawaiian Deep.

As the analysis of the earlier ("Gilbert") gravity data by Strange et al. is not materially affected by the additional ("Surveyor") data, these new data do not significantly alter the geological interpretation. The positive free-air anomaly near the proposed Moho Hole site can not be explained entirely by water-depth change and, as shown by Strange et al., can be recon-

ciled with the decrease in the depth to the Mohorovicic discontinuity.

Similarly, the more complete reduction of the magnetic data does not alter the gross picture presented by Malahoff and Woollard (in a forthcoming issue of *Pacific Science*) based on a preliminary reduction of the "Surveyor" data. As indicated by the depth analysis by Malahoff and Woollard, the depth of origin of the anomaly is somewhat greater (8.5 km) than the seismic depth to the Moho (5.8–7.0 km). The explanation for this discrepancy can be attributed to (*a*) the lack of precision in magnetic depth estimates, or (*b*) a difference in the depth at which there is a concentration of ferromagnetic minerals from gravity setting of heavy, early-formed minerals in an intrusion. Of the two explanations, the latter is considered the more probable in this case.

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